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Temperature Dependence of the Magnetoresistance of Co/Re Superlattices

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ABSTRACT

Hcp (10.0) Co/Re superlattices were grown by dc magnetron sputtering on sapphire (11.0) substrates with the [00.1] direction of the superlattice in the film plane. The temperature-dependent magnetoresistance (MR) was measured on samples patterned by photolithography from 10 K to 300 K in a 5.5 T superconducting magnet. The pattern allows the measurement of the MR with the current (I) and the magnetic field (H) parallel or perpendicular to the magnetic easy axis (c, the [00.1] direction). Measurements at 5 K on an antiferromagnetically-coupled sample shows dips in the MR near $H = 0$ when $H \parallel c$ and $H \perp I$, dips below the saturation value at H ~ 2.5 kOe for $H \parallel c$ and $H \parallel I$ configuration due to the competition between the anisotropic magnetoresistance (AMR) and the giant magnetoresistance (GMR). Since the AMR is dependent on the transport within the ferromagnetic layers, the temperature dependence yields information about the relative magnitudes of interface vs. bulk spin-dependent scattering. Our analysis shows that the GMR is anisotropic and that the spin-dependent scattering occurs predominantly at the interfaces only for certain configurations.

INTRODUCTION

Giant magnetoresistance (GMR), discovered in the late 1980's [1], which occurs in magnetic multilayers and nanoparticles, and the anisotropic magnetoresistance (AMR), extensively studied since the 1930's in bulk ferromagnetic materials [2], are effects that have been recently under intense scrutiny due to their technological applications. Only relatively recently, however, have these two effects been studied in the same system. Some previously studied systems with both AMR and GMR include Co/Cr [3], Fe/Cr [4,5], Co/Ru [6], Co/Cu [7,8] and Permalloy/Cu [9] multilayers. These include experiments which separate the AMR and GMR in the same system [7] and experiments which focus on the enhancement of the GMR by AMR in systems with magneto-crystalline anisotropy, like Co/Cr multilayers [3].

A topic of great current interest is determining the nature of the spin-dependent scattering responsible for GMR. Experiments where a monolayer or two of a magnetic material were added to the interface of a spin-valve [10] and the dependence of the GMR on interface roughness on Fe/Cr [4] show that in those systems the GMR depends strongly on scattering at the interfaces. But other studies show that the GMR depends on the film layer thickness [11], and that the GMR is dominated by bulk spin-dependent scattering [12].

Here we summarize the results of a recent, comprehensive study of the temperature-dependent magnetoresistance for a $[Co\ (1.7\ nm) / Re\ (0.7\ nm)]_{20}$ superlattice. The magnetoresistance, measured with the current applied in the plane of the sample, has been simulated assuming that the total magnetoresistance is the sum of a GMR and an AMR component. The AMR is known to be a result of spin-dependent scattering within the bulk of a ferromagnetic material. Hence, determining the relative amounts of bulk vs. interface spin-dependent scattering can be done by comparing the temperature dependence of the GMR contribution with that of the AMR

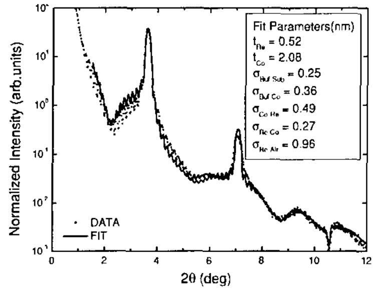

Figure 1. X-ray reflectivity of Co/Re superlattice using Cu Kα radiation. The results of the fit are shown above. The interface roughness parameters, indicated by σ, were extracted by fitting to an optical scattering model (see Ref. 13).

component. We show that when the current is applied parallel to the *c*-axis, the spin-dependent scattering is bulk-like, and when the current is perpendicular to the *c*-axis, the scattering depends on the interfaces.

EXPERIMENT

The superlattice's growth conditions, structural, and magnetic properties as well as neutron reflectivity measurements were reported previously [13,14]. In summary, the superlattice was grown via DC magnetron sputtering on Al_2O_3 (11.0) substrates with a 5.0 nm Re buffer layer. X-ray diffraction shows that the superlattice grows epitaxially in the hcp structure with the c-axis, hcp(00.1), in the film plane. Using low angle x-ray reflectivity techniques, the interface roughness between the layers was determined to be ~0.4 nm, as shown in Fig. 1. The superlattice is antiferromagnetically coupled with an in-plane magnetic easy axis parallel to the c-axis. Neutron reflectivity experiments, performed at the Intense Pulsed Neutron Source at Argonne National Laboratory, were consistent with the previous magnetic measurements and also show a gradual spin-flop transition when the external magnetic field is applied parallel to the c-axis. These

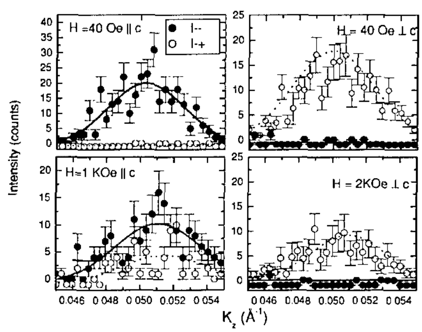

Figure 2. Non-spin flip (I--) and spin-flip (I-+) neutron scattering about the antiferromagnetic peak. The lines are fits to a Gaussian peak.

measurements were performed by scanning the antiferromagnetic peak and analyzing the spin of the scattered neutrons, as shown in Fig. 2. In this configuration, the spin-flip scattering intensity is proportional to the square of the component of the antiferromagnetic magnetization perpendicular to the applied field, whereas the non-spin-flip scattering intensity is proportional to the square of the component parallel to the field.

Magnetoresistance measurements were made using a cryostat with a 5.5 T superconducting magnet. The sample was patterned into an "L" shape using standard photolithography techniques [15]. One of the arms of the pattern was oriented parallel to the c-axis, while the other was perpendicular to it. This enabled us to apply the current both parallel and perpendicular to the magnetic easy axis on the same sample. Four-probe electrical resistance measurements using a constant current source and a nanovoltmeter were made in the following configurations: $H \parallel c / H \parallel I$, $H \parallel c / H \perp I$, $H \perp c / H \parallel I$, and $H \perp c / H \perp I$. This was done as a function of temperature from 5 K to 250 K and in an applied field H ranging from -3 T to 3 T.

RESULTS AND DISCUSSION

An important piece of information extracted from neutron reflectivity measurements is the vector direction of the magnetization in adjacent layers of cobalt with respect to the c-axis [14]. From this we can build an empirical model for the total magnetoresistance (MR) based on conventional definitions for the AMR and the GMR. It is known that the AMR depends on the angle the magnetization vector **M** makes with the sensing current **I**. This dependence can be written as

$$\rho_{AMR} = \rho_{\parallel} \cos^2 \gamma(\mathbf{H}) + \rho_{\perp} \sin^2 \gamma(\mathbf{H}), \tag{1}$$

where γ is the angle between **M** and **I**, $\rho_{\parallel}$ is the resistivity with $\mathbf{M} \parallel \mathbf{I}$ and $\rho_{\perp}$ is the resistivity with $\mathbf{M} \perp \mathbf{I}$.

Phenomenologically the GMR depends only on the antiferromagnetic alignment of the adjacent magnetic layers, so the GMR contribution can be written as

$$\frac{\rho_{GMR}(H) - \rho_{sat}}{\rho_{sat}} = A\left|\mathbf{M}_1(\mathbf{H}) - \mathbf{M}_2(\mathbf{H})\right|. \tag{2}$$

Here $\mathbf{M}_1$ and $\mathbf{M}_2$ are the magnetizations of adjacent ferromagnetic Co layers, $\rho_{GMR}(H)$ is the resistivity contribution of the GMR as a function of field, ρ_{sat} is the resistivity at saturation, and A is a proportionality constant.

In order to explain the magnetotransport data below, the angles that $\mathbf{M}_1$ and $\mathbf{M}_2$ make with

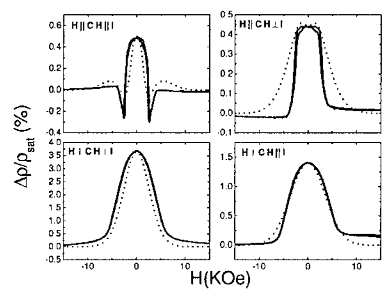

Figure 3. Magnetoresistance measurements (solid) and simulation (dotted) at 5 K. The simulation qualitatively matches the data.

respect to the current were *experimentally* determined from the neutron reflectivity measurements described above. Note that Eqn. 2 implicitly assumes a parallel resistor model where the spin-up and spin-down electrons scatter independently [16,17], and that the magnetic layers polarize the transport electrons. Eqn. 1 assumes a parallel resistor model that includes a spin-orbit interaction, which in turn causes the *s-d* electron scattering to be anisotropic [16]. The latter is the standard explanation for the existance of AMR in bulk ferromagnetic transition metals.

In Fig. 3 the MR dips at H = 1.5 KOe in the $H \parallel c$ / $H \parallel I$ geometry and dips at H = 0 in the $H \parallel c$ / $H \perp I$ geometry at 250 K. The MR also evolves differently as a function of temperature. We assume that $\mathbf{M_1(H)}$ and $\mathbf{M_2(H)}$ do not significantly depend on temperature since the dips in the MR remain at approximately the same field at all temperatures. This leaves all of the temperature dependence in the coefficient A and the ratio $\rho_\perp / \rho_\parallel$. By simulating the MR = AMR + GMR with the above equations, and using A and $\rho_\perp / \rho_\parallel$ as adjustable parameters, the data are qualitatively reproduced. Only one physical constraint was placed on the adjustable parameters in the simulation: that $\rho_\perp / \rho_\parallel$ must be the same for the current flowing along a given crystallographic direction because this ratio is proportional to the ratio of the spin up and spin down resistivities, which only depends on the crystallographic direction in which the current is flowing [16,17]. Our analysis shows that the interesting dips in the MR are only due to AMR [15]. The magnetoresistance of hcp(0001) oriented Co/Re multilayers has been found by other authors to be less than 2 % at 18 K [18], while our superlattices have a MR larger than 3.5 % at 5 K in certain geometries. In contrast to this previous Co/Re multilayer work, our samples are epitaxial, and therefore the AMR is more noticeable.

The existence of GMR in magnetic multilayer systems has been attributed to the matching of the band structure of the non-magnetic layer with either the spin up or spin down bands of the magnetic layer [19]. The small GMR value in Co/Ir superlattices has been blamed on the failure of the Ir bands to match with either the majority or minority spin bands of Co [20]. In the case of Co/Re, the bands of Re are similar to the spin down bands of Co [21]. This means that the GMR for Co/Re should be large, but we only find a GMR of approximately 2.5 % at 5 K. The low value of the GMR can be attributed to the large resistivity of the Re spacer. In other words, relatively few electrons traverse the Re spacer to the next Co-Re interface with out being scattered.

Notice that in Fig. 4(a) the temperature dependence of the AMR depends on the crystallographic direction that the current flows along. The GMR is usually thought to be isotropic,

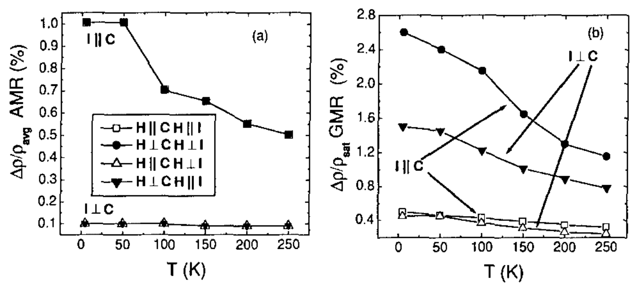

Figure 4. (a) Magnitude of the AMR $\Delta\rho_{AMR} / \rho_{avg}$, where $\Delta\rho_{AMR} = \rho_\parallel - \rho_\perp$, and (b) magnitude of the GMR $\Delta\rho_{GMR} / \rho_{sat}$, plotted as a function of temperature for different configurations.

but Fig. 4(b) shows that it is anisotropic with respect to both the field and current directions in our sample. Other authors[22] have also found the GMR to be anisotropic and to depend on the asymmetry in the spin-dependent resistivity ratio $\rho_{\uparrow} / \rho_{\downarrow}$ parallel and perpendicular to the current.

The AMR depends primarily on the transport through the ferromagnetic layers. On the other hand, in some studies the GMR depends on interface scattering [10], while in others bulk scattering has been shown to be important [12]. By comparing the temperature dependence of the GMR to the AMR (Fig. 5), one can determine whether the nature of the electron scattering is the same for the AMR and GMR. Since the AMR is known to be a result of scattering within the magnetic layers, differences between the AMR and the GMR must be due to differences in the electron scattering mechanism responsible for the two effects. In Fig. 5 the $I \parallel c$ geometry the curves are flat indicating the AMR and the GMR have a similar temperature dependence. This implies that when $I \parallel c$, bulk scattering is more important. If $I \perp c$, the temperature dependence for the GMR and AMR is different, meaning that interface scattering is more important. This is not entirely surprising given that the c-axis represents a strong crystallographic anisotropy, which leads to an anisotropic Fermi surface in the plane of the sample. This is confirmed by the inset of Fig. 5, which shows that the magnitude of the resistivity of the sample is very different in the two configurations.

Our simple empirical model, relying on $\mathbf{M}_1$ and $\mathbf{M}_2$ as functions of H determined from neutron reflectivity, does not take into account possible domain formation within the Co layers, which could alter the magnetoresistance [23]. This could explain why the model reproduces the qualitative features of the data, such as the dips near $H = 0$, but not the exact quantitative experimental results.

CONCLUSIONS

In summary, we have measured the temperature dependent magnetoresistance on a patterned, epitaxial Co/Re superlattice. We simulated the magnetoresistance and separated the AMR and the GMR effects for several temperatures. By comparing the temperature dependence of the AMR and the GMR, we find that in the $I \parallel c$ geometry the AMR and the GMR have the same temperature dependence, which implies that there is predominantly bulk scattering. In the $I \perp c$ geometry, the AMR and the GMR vary quite differently with temperature, implying that interface scattering dominates. Additionally, the GMR contribution is also found to be anisotropic. Finally, we note that other work, most notably in NiFe/Cu superlattices [24], has revealed similar behavior in terms of dips near $H = 0$ with $H \parallel c$ and $H \perp I$. We propose that the behavior observed in that instance is also due to the competition between the AMR and the GMR.

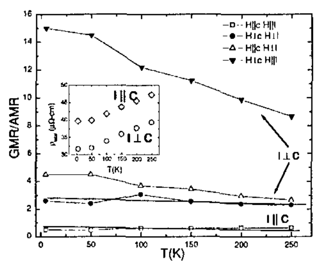

Figure 5. The ratio $\Delta\rho_{GMR} / \Delta\rho_{AMR}$ as a function of temperature. Inset is the total resistivity at $H = 0$ as a function of temperature for the $I \parallel c$ and $I \perp c$ geometries.

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